

FLUORINE IN A CARBON-ENHANCED METAL-POOR STAR

Simon C. Schuler^{1,2}, Katia Cunha^{1,3}, Verne V. Smith¹, Thirupathi Sivarani⁴, Timothy C. Beers⁴, AND Young Sun Lee⁴

ABSTRACT

The fluorine abundance of the Carbon-Enhanced Metal-Poor (CEMP) star HE 1305+0132 has been derived by analysis of the molecular HF (1-0) R9 line at $2.3357\ \mu\text{m}$ in a high-resolution ($R = 50,000$) spectrum obtained with the Phoenix spectrometer and Gemini-South telescope. Our abundance analysis makes use of a CNO-enhanced ATLAS12 model atmosphere characterized by a metallicity and CNO enhancements determined utilizing medium-resolution ($R = 3,000$) optical and near-IR spectra. The effective iron abundance is found to be $[\text{Fe}/\text{H}] = -2.5$, making HE 1305+0132 the most Fe-deficient star, by more than an order of magnitude, for which the abundance of fluorine has been measured. Using spectral synthesis, we derive a super-solar fluorine abundance of $A(^{19}\text{F}) = 4.96 \pm 0.21$, corresponding to a relative abundance of $[\text{F}/\text{Fe}] = +2.90$. A single line of the Phillips C_2 system is identified in our Phoenix spectrum, and along with multiple lines of the first-overtone vibration-rotation CO (3-1) band head, C and O abundances of $A(^{12}\text{C}) = 8.57 \pm 0.11$ and $A(^{16}\text{O}) = 7.04 \pm 0.14$ are derived. We consider the striking fluorine overabundance in the framework of the nucleosynthetic processes thought to be responsible for the C-enhancement of CEMP stars and conclude that the atmosphere of HE 1305+0132 was polluted via mass transfer by a primary companion during its asymptotic giant branch phase. This is the first study of fluorine in a CEMP star, and it demonstrates that this rare nuclide can be a key diagnostic of nucleosynthetic processes in the early Galaxy.

¹National Optical Astronomy Observatory/Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile; sschuler@ctio.noao.edu, cunha@noao.edu, vsmith@noao.edu

²Leo Goldberg Fellow

³on leave from Observatório Nacional, Rio de Janeiro, Brazil

⁴Department of Physics and Astronomy, Center for the Study of Cosmic Evolution, and Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI; thirupathi@pa.msu.edu, beers@pa.msu.edu, leeyou25@msu.edu

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1. INTRODUCTION

The single stable isotope of fluorine, ^{19}F , does not contribute nor is synthesized in the main nuclear reactions taking place in the cores of stars, and its abundance in the Universe is the lowest of all the light elements ($6 \leq Z \leq 20$). This and the notably limited number of atomic and molecular absorption lines in stellar spectra from which reliable abundances can be derived have made the nucleosynthetic origin of ^{19}F the least understood of all the light elements (Clayton 2003). Spectral features associated with the vibration-rotation transitions of the hydrogen fluoride molecule (HF) located in the near-IR K-band have proved to be the most accessible lines in stellar spectra, and the (1-0) R9 line at $2.3357 \mu\text{m}$, in particular, has been used in the analyses that have provided much of what is known about the nucleosynthesis and Galactic evolution of ^{19}F (Jorissen, Smith, & Lambert 1992; Cunha et al. 2003; Cunha & Smith 2005).

Based on theoretical calculations and scant observational data, three ^{19}F production sites have been identified. Woosley & Haxton (1988) first suggested that it is produced in Type II supernovae (SNe) by neutrino spallation on ^{20}Ne : $^{20}\text{Ne}(\nu, \nu'p)^{19}\text{F}$. In a pair of companion papers, Forestini et al. (1992) and Jorissen et al. (1992) provided evidence for ^{19}F production during shell He-burning in asymptotic giant branch (AGB) stars from the reaction $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$; the source of the protons primarily being $^{14}\text{N}(n, p)^{14}\text{C}$, with $^{13}\text{C}(\alpha, n)^{16}\text{O}$ providing the neutrons. Meynet & Arnould (2000) identified He-burning in Wolf-Rayet stars, where the same reactions as those in AGB stars could occur, as the third potential source. The contribution of each site to the evolution of ^{19}F in the Galaxy is not known, but the inclusion of all three sources in a Galactic chemical evolution model resulted in satisfactory agreement between the model prediction and the available observational data (Renda et al. 2004; Cunha & Smith 2005).

Despite the lack of detailed knowledge of Galactic ^{19}F production, observationally derived abundances of this rare nuclide provide valuable insight into the nucleosynthetic processes occurring in the Galaxy. Herein we present the results of our ^{19}F abundance analysis of the Carbon-Enhanced Metal-Poor (CEMP) star HE 1305+0132 (Christlieb et al. 2001). As currently defined, CEMP stars are stars with $[\text{C}/\text{Fe}] \geq +1.0$ (Beers & Christlieb 2005), and they fall into at least two general categories, those that exhibit large enhancements of s-process elements (CEMP-s) and those that do not have such enhancements (CEMP-no; Beers et al. 2007a). The origins of the chemical abundance patterns observed in CEMP-s

and CEMP-no stars, respectively, are thought to be pollution by mass transfer from a primary companion during its AGB phase and formation from a cloud that was chemically enriched by a previous generation of massive stars (Ryan et al. 2005; Aoki et al. 2007). Low-metallicity stellar evolution models have demonstrated that the C overabundances, as well as those of N and O, observed in CEMP stars can be reproduced by both of the proposed sources (e.g., Lau, Stancliffe, & Tout 2007; Hirschi 2007) and that the abundances of other elements, such as ^{19}F , may be used to distinguish them (Meynet, Ekström, & Maeder 2006). Indeed, Meynet et al. (2006) modeled a $7 M_{\odot}$ AGB star and a $60 M_{\odot}$ star, both with initial $[\text{Fe}/\text{H}] = -3.6$ and initial rotational velocities of $v_{\text{ini}} = 800 \text{ km s}^{-1}$, and the AGB model produced approximately 4 orders of magnitude more ^{19}F than the massive star model. This result implies that the derivation of ^{19}F abundances in CEMP stars can place robust constraints on their chemical histories and that ^{19}F may be a key diagnostic of nucleosynthetic processes at low metallicities. In this paper we describe the first investigation of ^{19}F in a CEMP star.

2. OBSERVATIONS AND ANALYSIS

Single-order echelle K-band spectra (2.3305 - 2.3400 μm) of HE 1305+0132 were obtained in 2007 March with the 8.1 m Gemini-South telescope using the NOAO Phoenix near-IR spectrometer in the $R = \lambda/\Delta\lambda = 50,000$ mode (Hinkle et al. 2002). A sequence of three integrations (1500 s each) was executed with the star positioned at three different locations separated by $4''$ along the slit. Calibration frames, including darks, flats, and a spectrum of a hot rapidly rotating star used for correcting telluric contamination, were also obtained. The raw 2-dimensional spectra were reduced to 1-dimensional spectra using routines in the IRAF software suite following the method described in Smith et al. (2002). The final co-added spectrum has a per pixel signal-to-noise ratio of 129.

The procedure employed to derive the stellar parameters and overall metallicity of HE 1305+0132 is fully recounted in Beers et al. (2007a) and is briefly described here. The effective temperature (T_{eff}) has been determined using published photometry and the color- T_{eff} calibrations of Alonso, Arribas, & Martinez-Roger (1996). We use the $(V - K)$ -based T_{eff} estimate as it has been demonstrated to be the best photometric indicator of T_{eff} for CEMP stars (e.g., Cohen et al. 2002). The V magnitude ($V = 12.57$) is taken from Beers et al. (2007b), and the K magnitude ($K = 9.814$) is from the Two Micron All Sky Survey Point Source Catalog (Skrutskie et al. 2006). From these data we find $T_{\text{eff}} = 4462 \pm 100 \text{ K}$. The logarithm of the surface gravity ($\log g = 0.80 \pm 0.30$ in cgs units) has been estimated from the Padova isochrones (Girardi et al. 2000), assuming a metallicity

of $[m/H] = -2.0$ and an age of 10 Gyr. A microturbulence (ξ) of 2.00 km s^{-1} has been assumed; the choice of ξ is of little consequence here as the derived ^{19}F abundance is not sensitive to its value.

The overall metallicity has been derived from medium-resolution optical and near-IR spectra of HE 1305+0132 obtained as part of a concerted program to estimate metallicities, CNO abundances, $^{12}\text{C}/^{13}\text{C}$ ratios, and potential s-process element enhancement for as many CEMP stars as possible (Beers et al. 2007a). A preliminary model atmosphere characterized by the adopted stellar parameters, enhancements of CNO typical for CEMP stars, and otherwise subsolar metallicity was generated with the ATLAS12 stellar atmosphere code (Kurucz 1996). The model atmosphere was then used to produce synthetic spectra in the wavelength regions covered by our medium-resolution optical and near-IR spectra. Comparisons of the synthetic and observed spectra provided new estimates of the metallicity and CNO enhancements, which were then used to generate a new model atmosphere. This process was carried out until both the optical and near-IR spectra were simultaneously fit satisfactorily. The final metallicity, CNO enhancements, and the associated uncertainties (as described in Beers et al. 2007a) are $[m/H] = -2.50 \pm 0.50$, $[C/Fe] = +2.20 \pm 0.35$, $[N/Fe] = +1.60 \pm 0.46$, and $[O/Fe] = +0.50 \pm 0.22$.

With the final ATLAS12 model characterized by the parameters described above and the line list from Smith et al. (2002) and Cunha et al. (2003), we used the LTE stellar line analysis package MOOG (Snedden 1973) to construct a synthetic spectrum of the $2.335 \mu\text{m}$ spectral region for comparison to the high-resolution Phoenix spectrum of HE 1305+0132. In addition to the HF line, there are features of particular interest to this and future analyses of the $2.335 \mu\text{m}$ region in the spectra of CEMP stars. These are a lone line at $2.3332 \mu\text{m}$ of the Phillips C_2 system and a handful of lines of the first-overtone vibration-rotation $^{12}\text{C}^{16}\text{O}$ (3-1) band head. These C_2 and CO features can provide estimates of the stellar C and O abundances, respectively, and the C_2 line in particular is a serendipitous benefit of observing CEMP stars in this spectral region. We have used the C_2 and CO features to derive the C and O abundances of HE 1305+0132; the fit to the C_2 line and one CO line are shown in Figure 1 and represent abundances of $A(^{12}\text{C}) = \log N(^{12}\text{C}) = 8.57 \pm 0.11$ and $A(^{16}\text{O}) = 7.04 \pm 0.14$. In Figure 2, we show the $2.3357 \mu\text{m}$ HF feature and the best synthetic fit, corresponding to an abundance of $A(^{19}\text{F}) = 4.96 \pm 0.21$. Synthetic spectra representing ^{19}F abundances ± 0.10 dex of the best-fit abundance are also shown in Figure 2. For each element, the quoted uncertainty is calculated by determining individually the sensitivities of the derived abundance to the adopted T_{eff} , surface gravity, C enhancement, and metallicity, and then summing in quadrature the resulting uncertainties associated with each parameter.

3. DISCUSSION

As is evidenced by Figures 1 and 2, our synthetic spectrum fits well the high-quality Phoenix spectrum of HE 1305+0132. The relative C and O abundances derived from fitting the Phillips C₂ line and the lines of the CO (3-1) band head are [C/Fe] = +2.68 and [O/Fe] = +0.88, and in both cases, the values are in agreement with those derived from the medium-resolution spectra within the combined uncertainties, which we note are considerable. The synthetic fit to the HF line is particularly sensitive to the model T_{eff} and C-enhancement, with a ± 150 K change in T_{eff} resulting in an abundance change of $\Delta A(^{19}\text{F}) = \pm 0.48$ and a ± 0.50 dex change in the model C-enhancement resulting in $\Delta A(^{19}\text{F}) = \pm 0.31$; the sensitivity to T_{eff} and C-enhancement dominate the total uncertainty in the final ^{19}F abundance. Raising the model T_{eff} and increasing the model opacity (increasing the C-enhancement) both effectively increase the temperature in the HF line-forming region, resulting in the higher derived ^{19}F abundances. The effect is also seen, although to a lesser degree, if the non-CNO metallicity of the model is increased, with a $\Delta[\text{m}/\text{H}] = +1.0$ change resulting in a $\Delta A(^{19}\text{F}) = +0.26$.

The ^{19}F abundance of HE 1305+0132 is remarkable. Adopting solar values from Asplund et al. (2005), $[\text{m}/\text{H}] = -2.5$, and the O abundance derived from our high-resolution spectrum ($[\text{O}/\text{H}] = -1.62$), the relative ^{19}F abundances are $[\text{F}/\text{Fe}] = +2.90$ and $[\text{F}/\text{O}] = +2.02$. Cunha & Smith (2005) and Cunha et al. (2003) have derived ^{19}F abundances of cool dwarfs in the Orion Nebula Cluster, as well as reanalyzed the ^{19}F abundances of K and M field giants from Jorissen et al. (1992), in order to investigate the evolution of ^{19}F in the Galaxy. Cunha et al. (2003) found the ^{19}F abundances of the field giants to fall nicely along the line of scaled solar abundance in the $A(^{19}\text{F})$ versus $A(\text{Fe})$ and $A(^{19}\text{F})$ versus $A(^{16}\text{O})$ planes, with scatter comparable to the analysis uncertainties. Cunha & Smith (2005) combined the red giant data with new Orion Nebula Cluster data in the $[\text{F}/\text{O}]$ versus $A(^{16}\text{O})$ plane, along with a chemical evolution model from Renda et al. (2004). The stars span less than 0.5 dex below the solar value in O abundance, but nonetheless the abundances of both stellar populations follow the chemical evolution model, which predicts a gradual decline in $[\text{F}/\text{O}]$ with decreasing $A(^{16}\text{O})$. The large overabundance of ^{19}F in HE 1305+0132 deviates significantly from the existing empirical data and the chemical evolution model of Renda et al. (2004), strongly suggesting that the origin of the ^{19}F in HE 1305+0132 lies outside of the standard Galactic chemical evolution channel.

HE 1305+0132 is the most Fe- and O-poor star- *by at least 1.5 orders of magnitude*- for which the abundance of ^{19}F has been derived, and while the bulk metallicity of HE 1305+0132, as defined by elements such as Fe, Ca, or Ti, is very low ($[\text{m}/\text{H}] = -2.5$), the ^{19}F and ^{12}C abundances are enhanced enormously relative to these other metals. Numer-

ous theoretical studies address the nucleosynthetic origins of the enhanced ^{12}C that defines CEMP stars (e.g., Meynet et al. 2006; Hirschi 2007; Tominaga, Umeda, & Nomoto 2007), with most efforts focused on two scenarios: mass transfer of processed material from a primary companion during its AGB phase and formation from material enriched by previous generation of massive stars. The overabundance of ^{19}F in HE 1305+0132 coupled to the overabundance of ^{12}C places the nucleosynthetic origin of these abundance anomalies squarely in the realm of the AGB stars. In Figure 3 the observed trend between $A(^{19}\text{F})$ and $A(^{12}\text{C})$ for MS, S, and C stars taken from Jorissen et al. (1992), as well as results for the hot He-stars from Werner, Rauch, & Kruk (2005), are shown. The Jorissen et al. sample contains both intrinsic thermally-pulsating AGB (TP-AGB) stars and stars that have been polluted by an AGB companion, and it is seen that both stellar types follow the same overall trend of increasing ^{19}F with increasing ^{12}C . The hot He-stars from Werner et al. (2005) are essentially the exposed cores of former AGB stars and reveal directly the products of He-burning during the phase of TP-AGB evolution. While there may be a systematic offset, or perhaps larger scatter, between the ^{19}F – ^{12}C trends as defined by the two studies, it must be noted that the hot He-stars have $T_{\text{eff}} = 90,000 - 200,000$ K, and their ^{19}F and ^{12}C abundances are derived from highly ionized (F VI and C III) lines. The MS, S, and C stars, on the other hand, have much lower temperatures ($T_{\text{eff}} = 3000 - 4000$ K) and have abundances derived from molecular lines of C_2 , CO, and HF. The similarity in the run of fluorine with carbon from these very different types of analyses provide strong evidence that one path for the nucleosynthesis of ^{19}F is tied to the production of ^{12}C during TP-AGB evolution.

The abundances of ^{19}F and ^{12}C measured here for HE 1305+0132 are also plotted in Figure 3 and fall right on the trend defined by the Jorissen et al. (1992) sample of red giants. Combined with the fact that the Jorissen et al. stars all have near-solar metallicities (~ -0.5 to $+0.5$ in $[\text{Fe}/\text{H}]$) while HE 1305+0132 has $[\text{m}/\text{H}] = -2.5$, the position of HE 1305+0132 in Figure 3 is evidence for efficient production of ^{19}F in metal-poor AGB stars. This efficiency is the result of two effects: the primary nature of the neutron source and the lack of heavy-metal neutron “poisons” in a low-metallicity environment. The neutron producing reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$ is fueled by ^{13}C synthesized via $^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}(\beta^+, \nu)^{13}\text{C}$ by the mixing of protons into primary ^{12}C produced by the triple- α process, making the resulting neutrons primary (i.e., independent of metallicity). The neutrons then take part in the proton producing reaction $^{14}\text{N}(n, p)^{14}\text{C}$, which then take part in the final reactions $^{18}\text{O}(\text{p}, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$. Because at low-metallicity the heavy elements that could compete for neutron captures are largely absent, the neutrons are very efficient at driving the final reaction chain necessary for ^{19}F production.

Indeed, Meynet et al. (2006) recently modeled a massive ($7 M_{\odot}$), rapidly rotating ($v_{\text{ini}} = 800 \text{ km s}^{-1}$), metal-poor ($[\text{m}/\text{H}] = -3.6$) AGB star and computed the chemical

composition of the envelope at the beginning of the TP-AGB phase; ^{19}F was found to be prodigiously produced, with a predicted envelope abundance of $[\text{F}/\text{Fe}] \approx +4.0$. While this predicted ^{19}F abundance differs from the observed value by about an order of magnitude, theoretical yields of low-metallicity stellar models are highly dependent on initial metallicities, masses, and rotational velocities (Hirschi 2007; Chiappini et al. 2006), and the mixing of the accreted material in the secondary star is not well understood. Thus, the near agreement is encouraging and should provide sufficient motivation to expand efforts to model low-metallicity AGB stars. Parenthetically, the near-agreement also suggests that rotation may have a significant impact on the nucleosynthetic yields of metal-poor stars.

The second hypothesis to account for the chemical composition of CEMP stars- formation from previously enriched material- must also be considered for HE 1305+0132. Models of the winds and SN ejecta of massive zero- and low-metallicity stars, like models of low-metallicity AGB stars, can effectively reproduce the enhanced CNO abundances observed in CEMP stars, but with regards to ^{19}F , no prodigious overproduction is seen. For example, Meynet et al. (2006) modeled a rapidly-rotating ($v_{\text{ini}} = 800\text{km s}^{-1}$) $60 M_{\odot}$ star at a metallicity of $[\text{m}/\text{H}] = -3.6$ and found that the star loses $\sim 40\%$ of its initial mass via winds over its lifetime, and that this wind material has a solar-scaled ^{19}F abundance ($[\text{F}/\text{Fe}] \approx 0.0$). Tominaga et al. (2007) performed hydrodynamic and nucleosynthesis core-collapse SN calculations of Population III ($Z = 0$) stars with main-sequence masses of 13 - $50 M_{\odot}$. Their SN model yields are consistent with the abundance patterns of very metal-poor stars in general, but in all of the calculations, ^{19}F is highly depleted ($[\text{F}/\text{Fe}] < -2.0$). The ^{19}F production seen in these two studies is typical of zero- and low-metallicity massive star nucleosynthesis models (e.g., Heger & Woosley 2002), and they seem to be unable to account for the highly enhanced ^{19}F abundance observed in HE 1305+0132.

The position of HE 1305+0132 in the $A(^{19}\text{F})$ and $A(^{12}\text{C})$ plane shown in Figure 3 soundly ties its nucleosynthetic history to that of TP-AGB stars and stars known to have been polluted by an AGB companion, and thus mass transfer from an AGB companion remains the preferred explanation for its observed abundance pattern. Accordingly, the abundances of the s-process elements are predicted to be enhanced in HE 1305+0132. Goswami (2005) and Gigoyan, Mickaelian, & Maun (2006) provide circumstantial evidence for this as they have independently identified HE 1305+0132 as a CH star, which are known as a group to be enhanced in s-process elements (Wallerstein & Knapp 1998); confirmation of this expected enhancement awaits a high-resolution spectroscopic abundance analysis. The derived large overabundances of ^{19}F and ^{12}C in HE 1305+0132, relative to the near-solar metallicity AGB stars from Jorissen et al. (1992) and Werner et al. (2005), are evidence that AGB star nucleosynthesis is highly efficient at low metallicities and point to the importance of AGB stars in the nucleosynthetic history of the early Galaxy.

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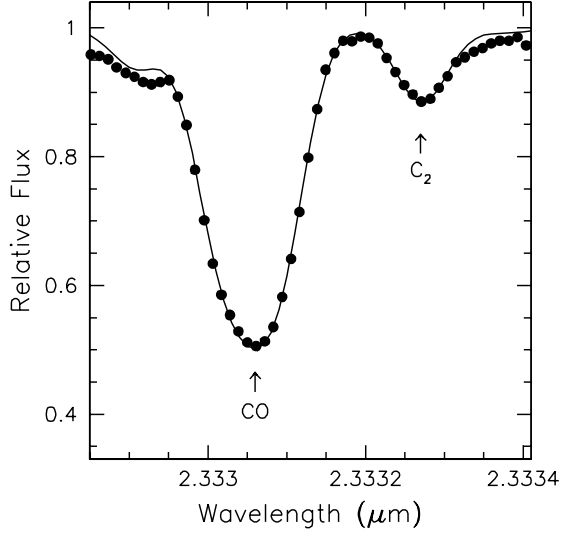


Fig. 1.— High-resolution near-IR Phoenix spectrum of HE 1305+0132 (filled circles) and the synthetic fit (solid line) of the 2.3331 μm region. The Phillips C₂ line at 2.3332 μm and a line of the first-overtone vibration-rotation $^{12}\text{C}^{16}\text{O}$ (3-1) band head are marked. This Phillips line is the sole C₂ line in our Phoenix spectrum.

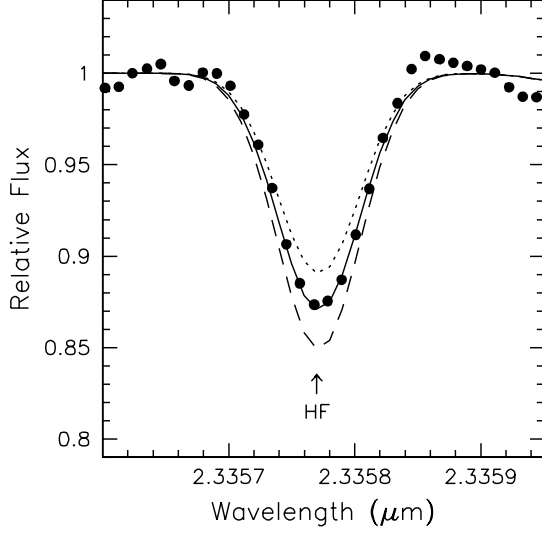


Fig. 2.— HF (1-0) R9 line at $2.3357 \mu\text{m}$. The observed high-resolution near-IR Phoenix spectrum is shown as filled circles, and the best-fit synthetic spectrum, representing a derived ^{19}F abundance of $A(^{19}\text{F}) = 4.96 \pm 0.21$, is given by the solid line. The broken lines are synthetic spectra characterized by ^{19}F abundances ± 0.10 dex of the best-fit abundance.

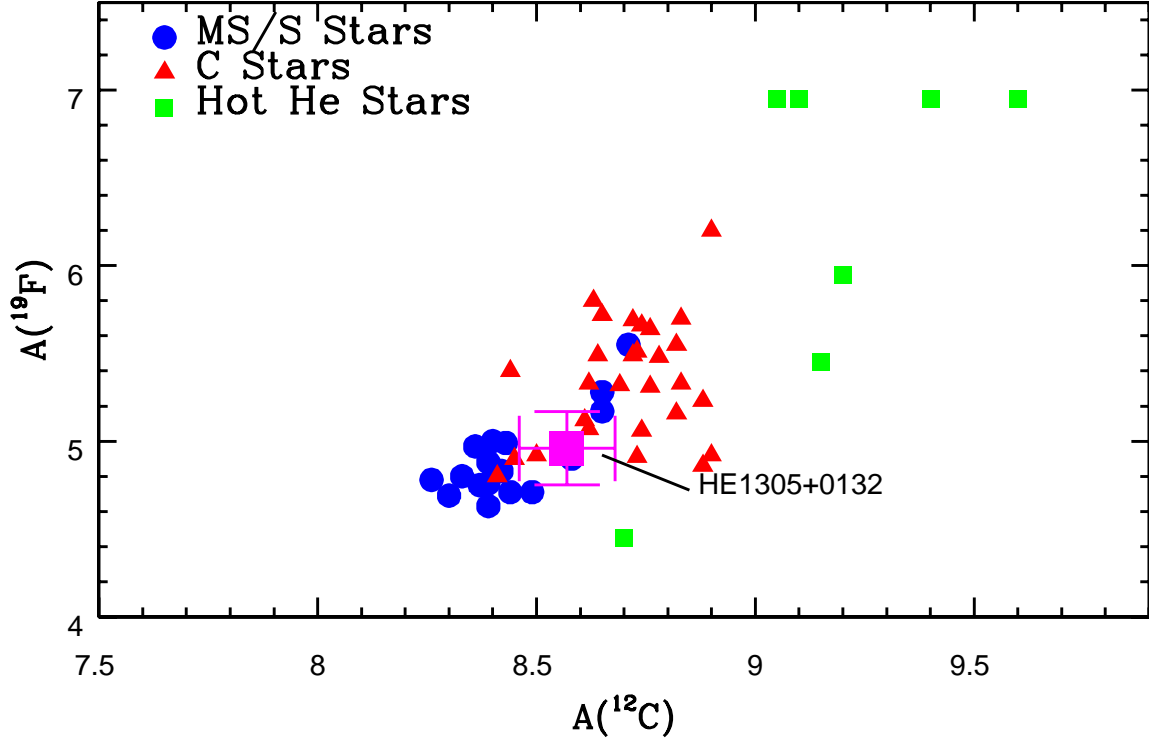


Fig. 3.— Logarithmic abundances of ^{19}F vs. ^{12}C . The abundances of HE 1305+0132 are marked by the magenta box with error bars.